Regional Climate and Atmospheric Hydrological Studies with TRMM Data

William K.-M. Lau[1], Huey-Tzu Jenny Wu[2], and Chung-Hsiung Sui[1]
lau@climate.gsfc.nasa.gov
[1]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[2]Science Systems and Applications, Inc., Lanham, MD 20776, USA

1. Regional water cycle and air-sea interaction

The Asian summer monsoon commences each year around mid-May over the South China Sea (SCS) and Indo-China region. In 1998, the Yangtze River Valley (YRV) flood associated with monsoon rainfall was one of the worst natural disasters on record. In the same year, the Tropical Rainfall Measuring Mission (TRMM) satellite made its first boreal summer observations. In this study, we use TRMM data to investigate the variability of regional water cycle and air-sea interaction associated with the evolution of Asian summer monsoon. We conducted identical analysis for summer months of 1998 and 1999. As a demonstration, only results for May 1998 are shown.

TRMM data used in this study are daily mean rain rate (2A12) constructed from TRMM Microwave Imager (TMI) surface rain rate with a 0.25^{o} horizontal resolution, as well as the sea surface temperature (SST) derived from TMI by Wentz et al. of Remote Sensing Systems. Other data used include scatterometer wind at 10 m derived from SSM/I data (Atlas et al. 1996), rain rate from TRMM Goddard Profiling algorithm (GPROF) and NOAA daily outgoing longwave radiation (OLR).

Figure 1 shows the evolution of the large-scale surface wind and the GPROF rain rate during May 1998. The most pronounced feature is the development of the double cyclones accompanying intense rain straddling the equator on May 14. At the same time, a mid-latitude frontal system was established and anchored over southeastern China and Taiwan at the northwestern rim of the West Pacific Anticyclone. On May 19, the northern cyclone developed into a major monsoon depression over the Bay of Bengal coinciding with the southeastward propagation of the mid-latitude frontal system into SCS, triggering the onset of SCS monsoon. A recent study by Lau and Li (2001) indicates that the SCS was a major moisture source to the torrential rain over the YRV in mid-June 1998.

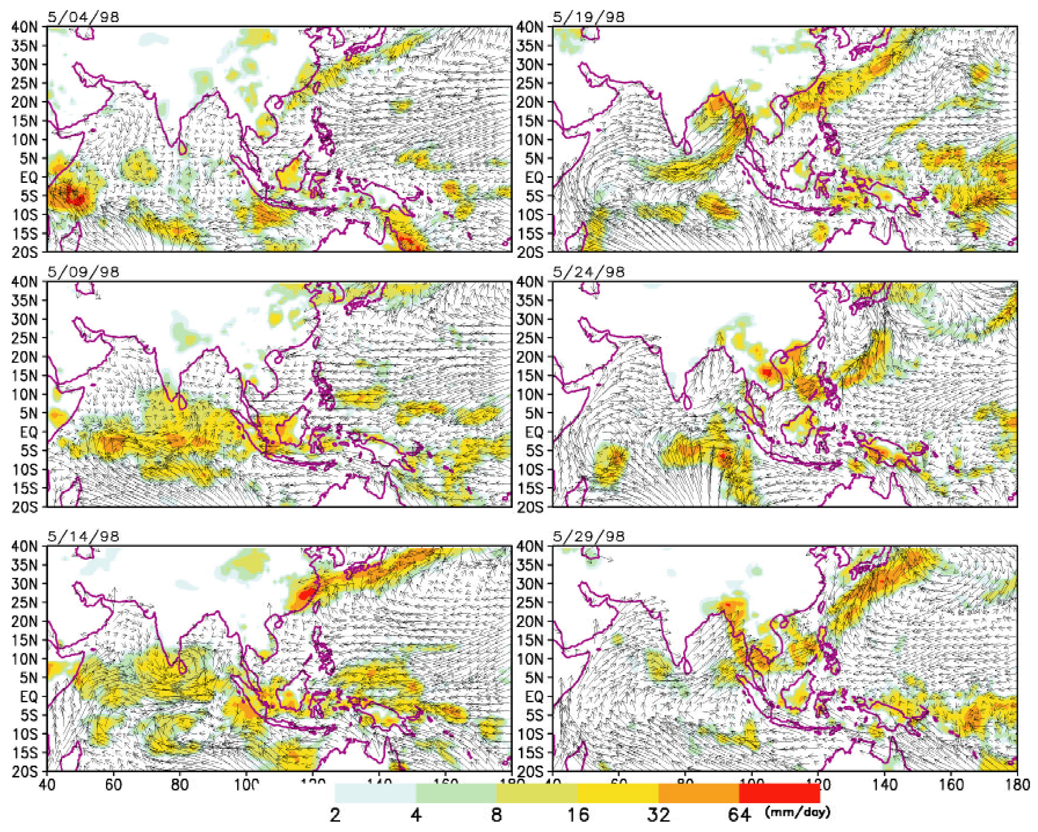

Fig. 1 Daily-mean surface rain rate from TRMM GPROF and surface wind from SSM/I for May 4 to 29, 1998

The convective complex over the Indian Ocean during the pre-SCS monsoon period can be identified with eastward propagating supercloud cluster associated with the Madden Julian Oscillation (MJO). The eastward propagation along the Equator and the northward propagation along the Bay of Bengal of the MJO is well illustrated in Figure 2. Heavy TMI rain rate (> 16 mm/day) is predominantly confined within the 200 w/m^2 OLR contour line, which depicts the area of deep convection.

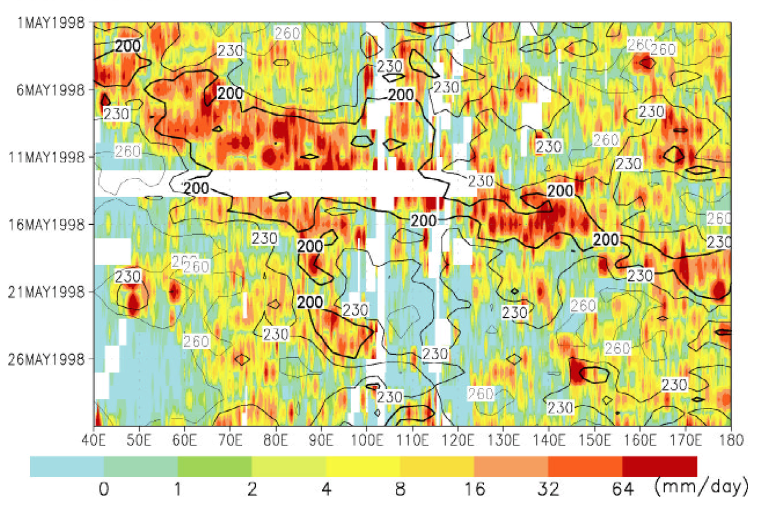

Fig. 2a Time longitude cross section of the mean values of 5 ^{o}S to 5 ^{o}N of TMI daily surface rain rate (shaded) superimposed with OLR (contoured, w/m²)

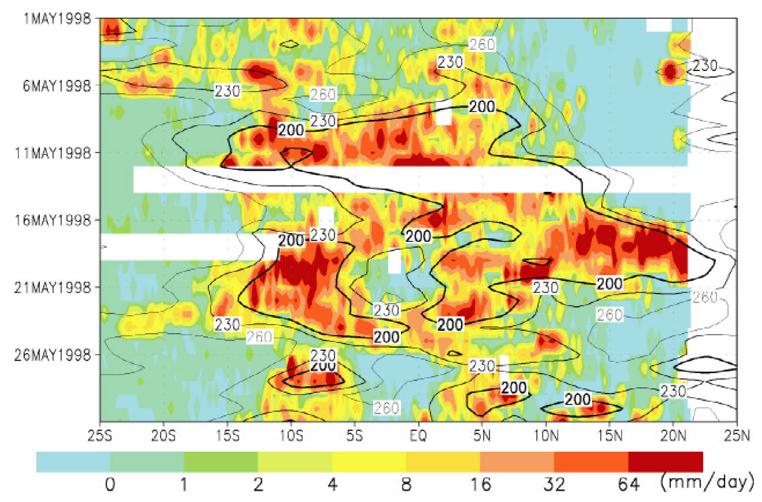

Fig. 2b Same as Fig. 2a, but for time latitude cross section of the mean values of 85-95 ^{o}E

To calculate the water cycle associated with the evolution of Asian monsoon requires knowledge of many parameters. Among them, TRMM can provide the rain rate and column water vapor. Also required is the vertical profile of wind and moisture fields, which can be estimated by combining the NCEP reanalysis product and the SSM/I and QuickScat wind product. Figure 3 shows an example of how the precipitation may relate to the wind field. On both May 14 and 19, heavy rain rate occurred mostly over areas of convergent wind, indicating the importance of the moisture convergence term in the calculation of water budget of Asian monsoon.

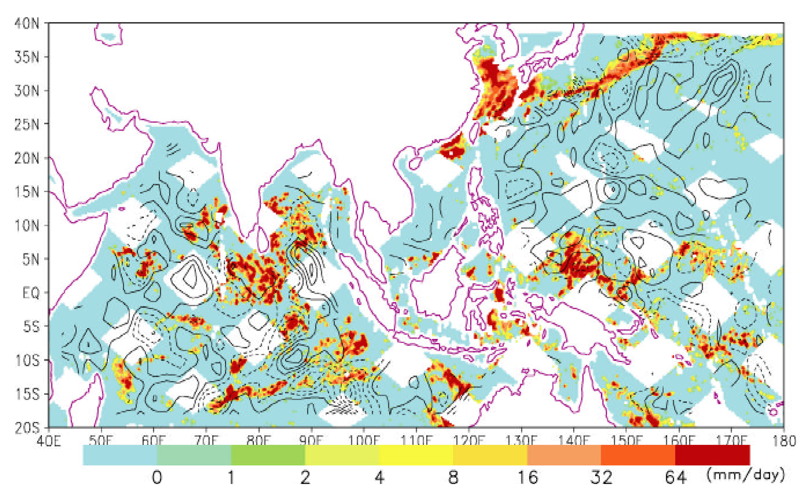

Fig. 3a TMI daily surface rain rate (shaded) superimposed with the divergence field of SSM/I surface wind (contoured, solid lines for positive and dash-lines for negative values) on May 14, 1998.

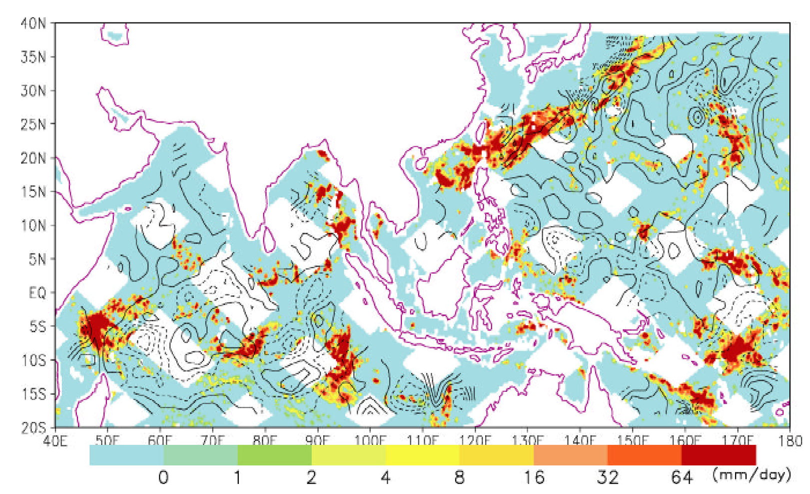

Fig. 3b Same as Fig. 3a, but for May 19, 1998. Note solid contour lines depict divergent wind and dashed lines convergent wind.

Before the Asian monsoon starts in early May, the SST over the Indian Ocean can reach as high as 31ºC. In this study, we will investigate how this extreme warm Indian Ocean nourishes and interacts with Asian monsoon. Figure 4 shows an example of the regional air-sea interaction. On both May 14 and 19 of 1998, the change of SST was highly correlated with surface wind field, indicating the importance of evaporative cooling.

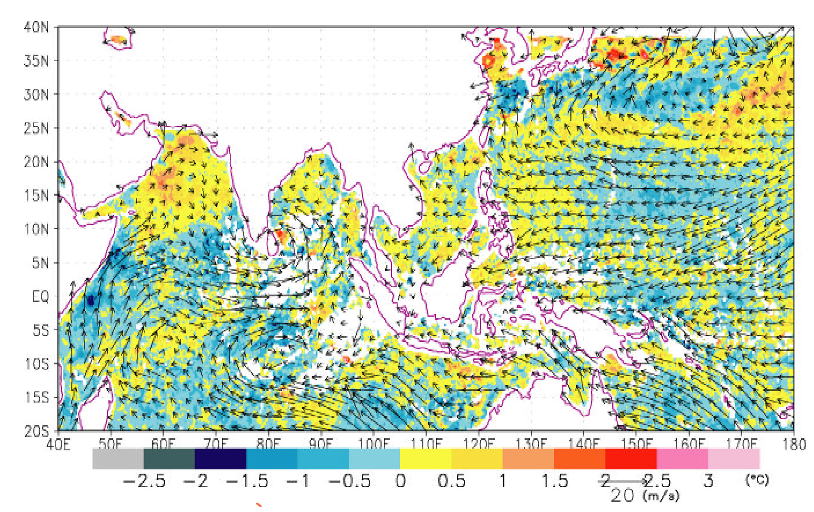

Fig. 4a Change of SST (dSST) (shaded) superimposed by the SSM/I surface wind (vector) on May 14, 1998. dSST on a certain day is calculated by the difference in the 5-day running mean values of TMI SST two days after and two days before that particular day.

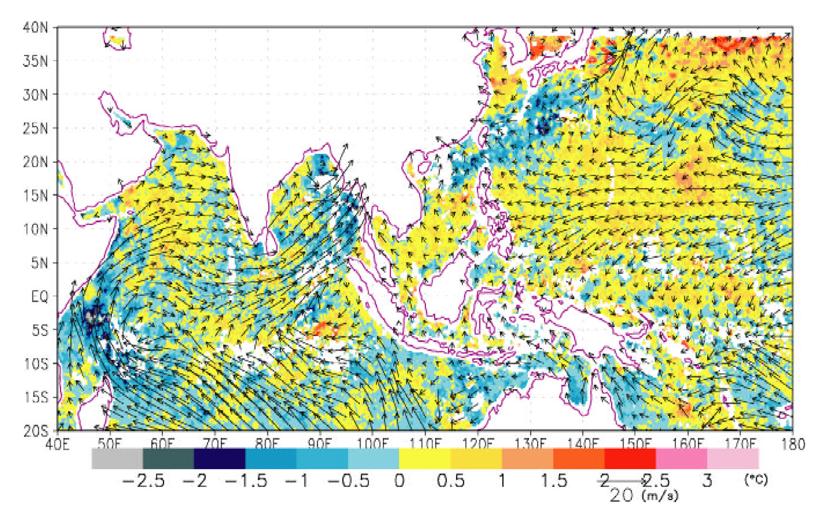

Fig. 4b Same as Fig. 4a, but for May 19, 1998.

2. Hydro-climate feedback processes

Key scientific questions:

- *How does the global hydrologic cycle (rain, water vapor, and clouds) respond and feedback to surface warming?*
- *What are the relative roles of large scale circulation and SST?*

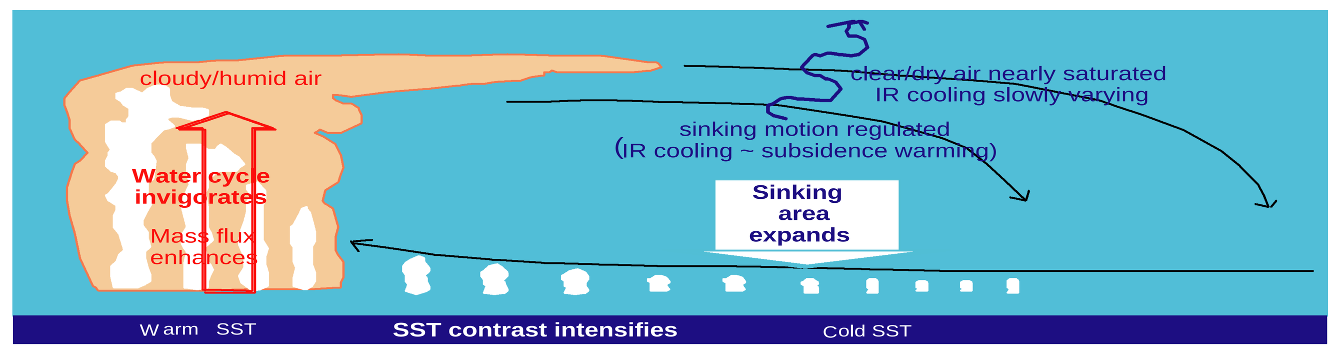

Fig. 5 Schematic diagram showing interactions among hydrologic cycle, large scale circulation, and SST.

Figure 6 shows the TMI rain as a function of SST in the western Pacific (WPAC), the central Pacific (CPAC), and the eastern Pacific (EPAC). During the warm event of 1998, the 28 ^{o}C threshold of convective precipitation is quite obvious in all three regions. During the cold event of 1999, precipitation tends to occur at lower SST in CPAC and EPAC, likely due to the presence of more stratiform rains.

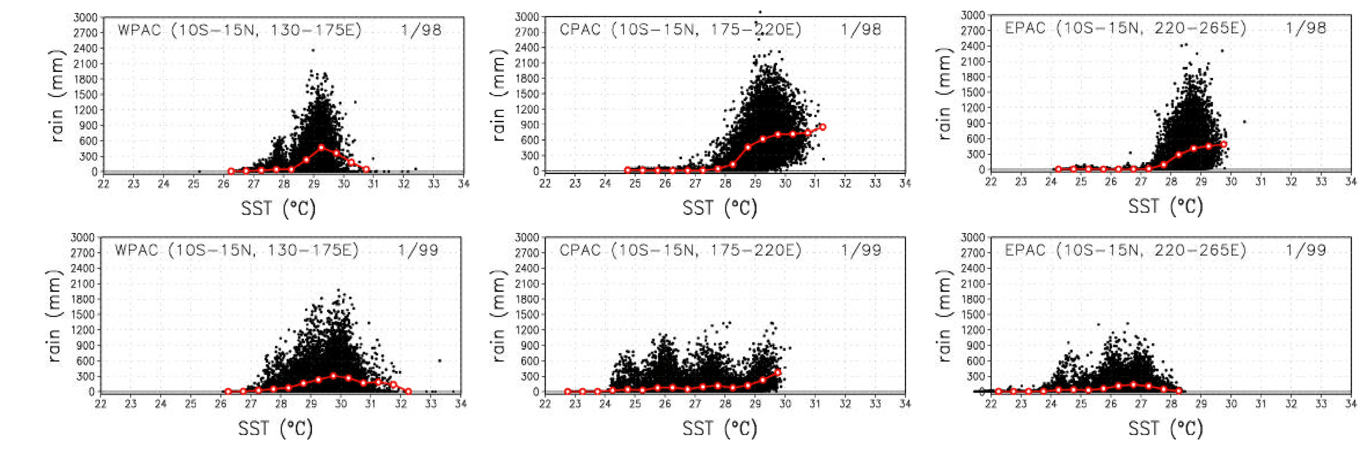

Fig. 6 Scatter diagram of collocated monthly mean SST and monthly accumulated rain, with mean rain values superimposed.

An analysis of daily hydrologic variables from TMI shows that a positive correlation between SST and cloud water (CW), rain rate (RR), and precipitable water (PW), but a negative correlation between SST and cloud amount (CA) (see Fig. 7).

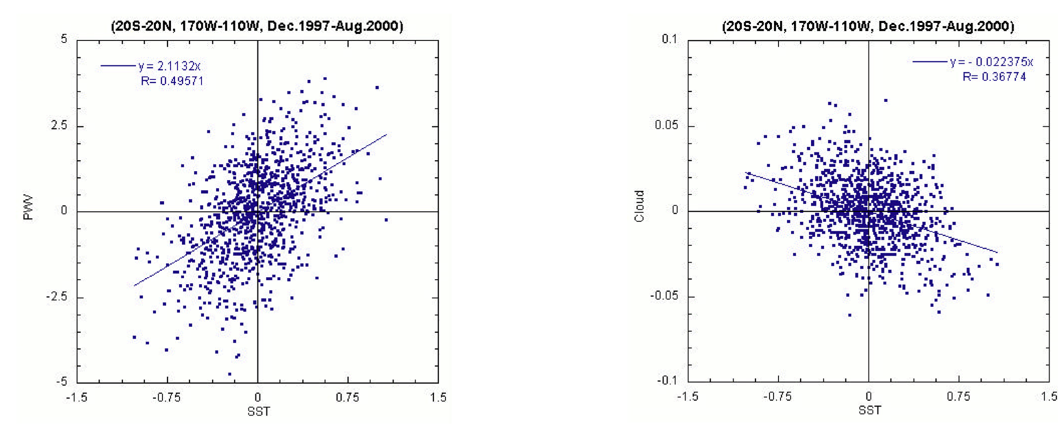

Fig. 7 Mean column water vapor and cloud amount over the cloudy areas (CW > 0.12 mm) as a function of the corresponding mean SST within the tropical Pacific (20^{o}S-20^{o}N, 130^{o}E-110^{o}W) for the period of Dec. 1997 - Aug. 2000.

Hypotheses

The negative relationship between cloud amount and SST is due to:

a. Cirrus detrainment from cumulus convection diminishes with higher temperature (Lindzen et al., 2001).
b. Cloud shielding effect -- reduced cloudiness causes increasing solar radiation, in turn causing warmer SST (Lau and Sui, 1997).
c. More ice particles are produced in colder temperature. Because of their lower densities, they are less likely to precipitate, hence more high clouds (this study).

Some preliminary evidence in support of hypothesis (c)

An estimate of the residence time of cloud, $t_{cw} \sim [(1/CW)(dCW/dt)]^{-1} \sim CW/RR$, has been calculated based on vertically integrated TRMM cloud budget. The residence time decreases with increasing SST in the stratiform cloud regime (RR < 1 mm hour^{-1}) but is independent of SST in the convective regime (RR > 5 mm hour^{-1}). This suggests that the recycling rate in stratiform cloud regimes (mostly ice) may be a fundamental cause of the increases of mean cloudy area over cold SST. This is supported by the analyses shown in Figures 8 and 9. Fig. 8 shows that there are more (less) high clouds over the warm (cold) SST in the western Pacific during the period of March 19-23 (March 9-14) resulting in a positive cloud-SST relation shown in Fig. 9a. But high clouds over cold SST in the eastern Tropical Pacific contribute to a negative cloud-SST relation shown in Fig. 9b.

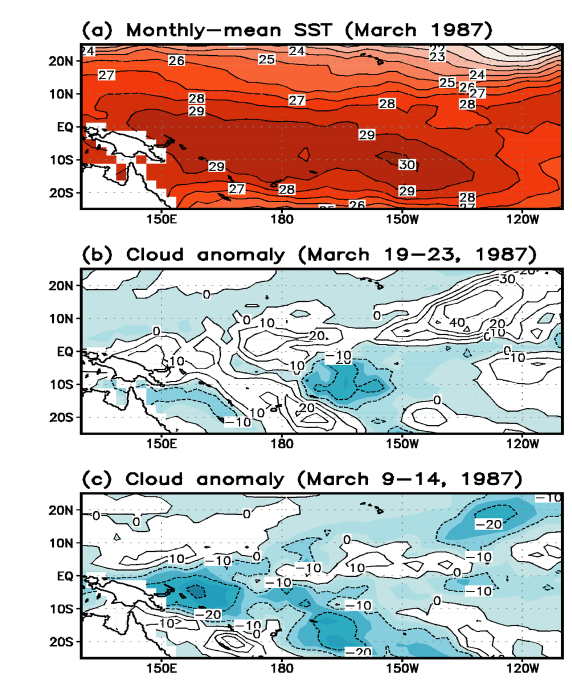

Fig. 8 (a) Spatial distribution of monthly-mean SST on March 1987. (b) Cloud anomaly from monthly mean for March 19-23, 1987. (c) Cloud anomaly for March 9-14, 1987.

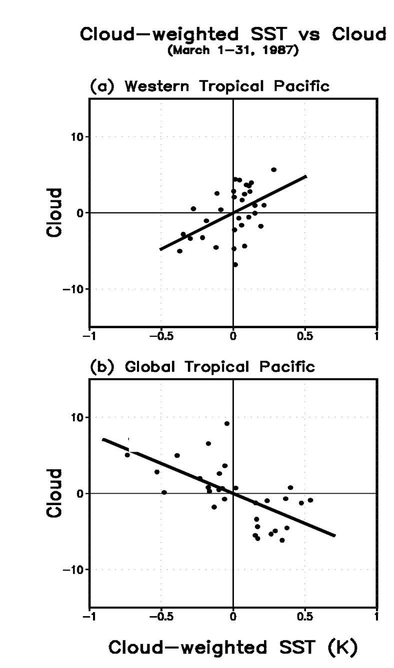

Fig. 9 Scatter plot of cloud-weighted SST and domain-mean cloud for March 1987 over the western tropical Pacific (a) and the global tropical Pacific (b).

Summary

Our analyses of TRMM data indicate that there is an increase in total rainfall, water vapor, and cloud liquid water in the tropical atmosphere as a result of increasing SST, consistent with atmospheric thermodynamics. However, a negative relationship exists between cloud amount and SST, suggesting that in a warmer climate there may be a reduction in high-level (ice) clouds.

References

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